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The Multiple Discipline Group (MDG) was formed to bring together diverse elements of the University of Washington and other institutions to work on oceanographic and acoustic problems. The work of the MDG includes experimental, numerical and theoretical investigations of surface scattering, of wave propagation in random media (WPRM), and of the physics of shallow water acoustic propagation. Currently the MDG is a recognized element of the Applied Physics Laboratory reporting to the Deputy Director of APL. An Executive Committee (Terry Ewart, Frank Henyey, Darrell Jackson, Robert Porter, Eric Thorsos and Kevin Williams) sets policy and recommends and approves the collaborative programs under the aegis of the MDG. Terry Ewart is the current Chairman. The research discussed here will be continued during the tenure of the MDG five year grant to Terry Ewart (FY94-FY98).

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ROBERT J. SILVERMAN

MULTI-DISCIPLINE OCEAN ACOUSTIC SCATTERING PROGRAM
Final Report for N00014-90-J-1260 (10/1/89 to 3/31/94 - Prepared 5/31/95)

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ABSTRACT

The Multiple Discipline Group (MDG) was formed to bring together diverse elements of the University of Washington and other institutions to work on oceanographic and acoustic problems. The work of the MDG includes experimental, numerical and theoretical investigations of surface scattering, of wave propagation in random media (WPRM), and of the physics of shallow water acoustic propagation. Currently the MDG is a recognized element of the Applied Physics Laboratory reporting to the Deputy Director of APL. An Executive Committee (Terry Ewart, Frank Henyey, Darrell Jackson, Robert Porter, Eric Thorsos, and Kevin Williams) sets policy and recommends and approves the collaborative programs under the aegis of the MDG. Terry Ewart is the current Chairman. The research discussed here will be continued during the tenure of the MDG five year grant to Terry Ewart (FY94-FY98)

LONG RANGE OBJECTIVES

Our long term objectives are to improve our understanding of how deterministic and stochastic ocean surface, volume, and bottom scattering processes affect acoustic propagation and reverberation in the ocean, and to develop models from which direct predictions of acoustic fluctuations can be made. Another long-range objective is to develop rigorous and experimentally tested methods for numerically simulating ocean acoustic scattering. These techniques can then serve as testbeds for more efficient (and possibly less accurate) simulation models.

INTRODUCTION

At the beginning of this contract period, the MDG was working on 2 large experimental programs in addition to the ongoing science program. This Grant supported the science involvement in these projects to refine the experiment/hardware designs. In the first of these experiments we were participating in the design of the Geodesic Underice Tramway System (GUTS). GUTS was designed to carry an instrumented buoyant carrier under the ice along precise x,y,z trajectories with respect to the ice canopy. The apparatus was completely designed and approximately 1/3 completed when the project was canceled due to downsizing of the ONR high latitude research budgets. Many scientific missions were being considered for GUTS: the MDG effort

was focused mainly on correlating detailed characterization of the elastic, compressional, and trapped air and brine properties of the ice with deterministic measurements of the reverberation at several frequencies. The project funding ended with FY92 after the expenditure of $710K; the equipment has been placed in storage. A final, more detailed, report on GUTS is available.

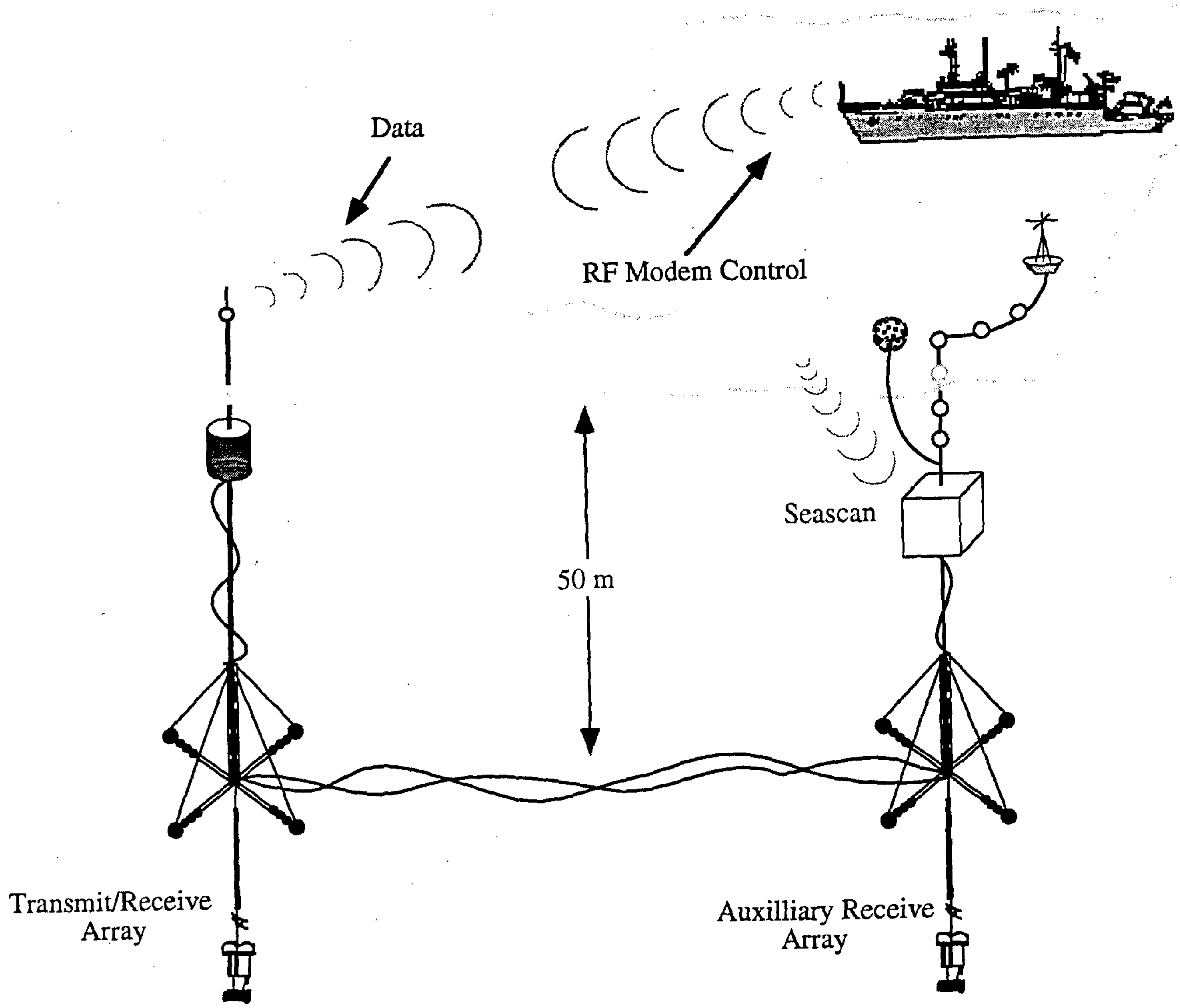
The second large experimental program was the design and construction of the Pencil Beam apparatus, which was designed to make backscattering measurements from the ocean surface and compare the results with direct measurements of the near-surface-zone wave and bubble field. A final, more detailed, report on the Pencil Beam is available. The project was canceled after the expenditure of $1,200K. The hardware completed was put in storage; the apparatus design was nearly completed. Prototype 400Hz transmitting transducers were designed, built, and tested in local waters. Thirty operational 400Hz transmitting transducers were built at APL. An acoustic system that we term "Acoustic Legos" was designed.

The CAscadia Basin EXperiment (CABEX) was funded through ONR code 124 to utilize the transmitters and the "Acoustic Legos" to make a surface backscattering experiment with reduced scope in comparison to the Pencil Beam project. Funding for the scientific effort was supported by this grant. We operated an array of sources and receivers at 400 Hz simultaneously with the operation of David Farmer's SEASCAN. The CABEX array shown in Figure 1 allows us to make a spatially diverse source and receiver image of the near surface zone backscattering at 400 Hz. SEASCAN makes a sweep of the surface zone out to several hundred meters using high frequency to locate the bubble clouds. To date, the analysis has demonstrated that our imaging algorithms work well with a test point target (Lexan sphere). SEASCAN was inoperative during most of the operation of CABEX. The analysis will be completed using FY95-FY96 MDG funding

The MDG at the University of Washington's Applied Physics Laboratory is composed of oceanographers, physicists, acousticians, mathematicians, applied mathematicians, statisticians, and electrical and mechanical engineers. Each topic we are addressing includes theoretical, numerical and experimental components. We believe that our broad focus has provided the intellectual breadth to make real progress in answering difficult questions that arise where oceanography and acoustics, theory and numerics, and experiment and predictions interface. The MDG investigators and their specialties are listed in Table I. Ten graduate students were associated with the program during the contract period. In addition to scientists at the University of Washington, the MDG works closely with David Farmer and his colleagues at the Institute of Ocean Sciences (IOS), B.C., Canada. Barry Uscinski of the Department of Appled Mathematics and Theoretical Physics, University of Cambridge, UK, collaborates with the MDG on theoretical issues, and spends one month per year at APL. Charles Macaskill of the University of Sydney in Australia has a long history of working with the Group and has spent time at the University of Washington working on surface and volume scattering issues. The collaborations range from separately funded elements to Co-Investigator status on grants.

Table I. Investigators in the Multi-Discipline Group FY89-94

Investigator	**Discipline**	**Affiliation**
John Ballard	Mathematics	APL (Resigned '94)
Eric D'Asaro	Oceanography	APL & School of Oceanography
Terry Ewart	Physics	APL, Sch. of Ocean. & Elec. Eng. Dept.
David Farmer	Oceanography	Inst. Oc. Sci., B.C. Canada
Mike Gregg	Oceanography	APL & School of Oceanography
Jim Grochinski	Physics	APL
Frank Henyey	Physics	APL & Physics Dept.
Antje Horing	Physics	Physics Department (Resigned '94)
Darrell Jackson	Physics	APL & Elec. Engr. Dept.



CABEX II Experiment - November, 1993

Figure 1. CABEX II experiment layout

Peter Kaczkowski	Elec. Engr.	APL
Le Olson	Mech. Eng.	APL
Don Percival	Statistics	APL & Stat. Dept. (Inactive '94)
Robert Porter	Elec. Eng.	APL & Elec.Eng. Dept.
Steve Reynolds	Oceanography	APL
Jim Riley	Mech.Engr.	Mech. Engr. Dept. & Appl. Math. Dept.
Jim Ritcey	Elec. Engr.	Elec. Engr. Dept.
Dan Rouseff	Elec. Eng.	APL
Kevin Williams	Physics	APL
Charles Macaskill	Appl. Math.	Univ. of Sydney, Australia & APL
Eric Thorsos	Physics	APL & Elec. Engr. Dept.
Barry Uscinski	Physics	Univ. of Cambridge, U.K. & APL
Kevin Williams	Physics	APL
Kraig Winters	Appl. Math.	APL & Appl. Math. Dept.

Graduate Students	**Discipline**	**Advisor**
Dashen Fan	Elec. Eng.	Ewart (Graduated '92 MS)
Scott Gordon	Elec. Eng.	Ritcey (Graduated '94 MS)
Eric Hirst	Mech. Engr.	Riley/Ewart (Summer '95)
Peter Kaczkowski	Elec. Engr.	Thorsos (Graduated '94 PhD)
John Litherland	Elec. Eng.	Ewart (Graduated '90 MS)
Garfield Mellema	Elec. Eng.	Ewart
Miguel Nathwani	Physics	Henyey
Celt Schira	Elec. Eng.	Ewart (Resigned '94)
Doran Weisbarth	Oceanography	Ewart (Resigned '91)
Qian Wen	Elec. Eng.	Jackson (Resigned '94)

SupportPersonnel	**Discipline**	**Role**
Michael Kenney	Computer Scientist	Software & Systems Support
Vern Miller	Mech. Eng.	Mechanical Design
Nancy Sherman	Business	MDG Coordinator
David VanEss	Elec. Eng.	Electronic Design

Kraig Winters and Daniel Rouseff received PhD's in Applied Mathematics (Advisors D'Asaro/Ewart) and Electrical Engineering (Advisors Porter/Ewart) in 1989 on earlier MDG work.

PROGRESS

Since the MDG was formed, we have been producing software tools that are based on various elements in our research program (summarized in Table II). We possess most of these tools in validated form, available for use in all of the MDG research programs. The codes were developed on our Stardent mini-Supercomputer, but can be run on Cray (or other) machines. Each topic will be presented subsequently in some detail.

Table II. MDG Software Tools

Topic	Status	Comments
Parabolic Equation		Most of the following can be combined.
Narrow Angle	C	General - used in all codes.
Wide Angle	C	General - used in all codes.
Stochastic	C	Many stochastic input models - can use Ocean Medium (below).
Point Source	C	Many types available.
Wide Band	C	Used for pulse propagation and other time domain studies.
Polar	C	Several media - used for stochastic point source studies.
Surface	C	Can input any surface wave model.
Backscattering	O	Combines forward scattering with surface backscatter.
Ocean Medium		Joint with D'Asaro and Winters - internal waves (IW).
Navier Stokes	C	3-D - Reproduces time/space stochastic non linear IW.
Linear IW	C	Uses linear IW dispersion relation - stochastic 3-D + time.
Vertically Lagrangian	C	Simple nonlinear model.
Near Surface	C	2-D - Used to simulate surface bubble clouds - Farmer.
Ray Tracing		Solution of Eikonal Differential Equation
Helmholtz	C	Range dependent profile - analytic SSP.
Parabolic	C	Range dependent - needed when comparing PE wave fields.
Numeric SSP	O	Will work with Ocean Medium models above.
Mode Propagation	T	Range Independent PE and Helmholtz.
Wigner Function	T	Used to study angle/depth or frequency/time signals.
Semi-Classical Waves calculations.	O	Fast method for Wigner distribution and other
4^{th} Moment Theory		Many versions available.
Plane Wave	C	Many different media - good agreement with PE above.
Point Source	C	Many different media - validated with MATE/PE simulations.
Imaging		For surface backscatter e.g., CABEX/Pencil Beam.
Point Scatterer	O	Images largest "events" tested with simulations.
Bartlett	C	Linear beamformer - tested with simulated bubble distributions.
3^{rd} Moment	C	Tested with simulated bubble distributions.
Minimum Variance	C	Tested with simulated bubble distributions.
Pulse Analysis	C	Implementation of Bell-Ewart multipath separation algorithm.
Integral Equation	C	Thorsos' integral equation surface scattering code.

(C indicates completed and tested, T indicates that testing is ongoing, and O indicates ongoing development.) In addition to the software tools developed, we completed a system that is capable of making single frame animation super VHS video movies directly from simulation results. This system is important for visualizing the complex space/time variability in the simulated processes.

The following are brief accounts of the MDG research efforts including progress for the period of the Grant and ideas for the future.

Surface Zone Scattering

Numerical work on surface zone scattering has focused on developing and applying parabolic equation (PE) simulations that account for both rough interface scattering and bubble cloud scattering (volume scattering) occurring near the surface. At present, the surface roughness is taken as one-dimensional. In the PE approach to forward interface scattering, originally developed by Tappert and Nghiem-Phu, the propagating field obeys

the pressure release boundary condition on rough surface realizations. It therefore automatically gives the correct surface forward scattered field in the PE approximation. We have also made the extension to a wide angle PE method. Accuracy has been confirmed by making detailed comparisons with exact results based on integral equation solutions. These comparisons were done in conjunction with a separate project entitled, "Numerical Studies of Rough Surface Scattering" (E.I. Thorsos, PI). The PE simulations for interface scattering have also been extended to surface backscattering, but for most sea state and frequency conditions scattering from bubble clouds will dominate interface backscattering.

The combined effects of volume and surface interface scattering have been studied in the forward scattering case at low frequencies (200-400 Hz). We have developed a stochastic method for generating realizations of tenuous bubble clouds near the surface. Bubble cloud data of Farmer and co-workers are used to determine the model parameters. Our PE simulations, which include propagation through the bubble field and scattering from the rough interface, show how the acoustic field near the surface is changed as the void fraction in tenuous bubble clouds is increased. This is important to study because backscattering calculations from tenuous clouds are most easily done using lowest order perturbation theory, that is, ignoring the change in the field structure caused by the bubble clouds; thus, it is necessary to know when this approximation is accurate. With the PE simulations we can then see directly when the perturbation approach to calculating scattering from tenuous bubble clouds breaks down. We find this occurs when the average void fraction at the surface exceeds about 10^{-5}, not an unreasonable level for high sea state conditions. The simulations also show that the forward propagating field becomes more structured in this regime, leading to a reduction in the vertical correlation length of the field in comparison to scattering from the rough interface alone. This may have significance for sea surface forward scattering, especially at the somewhat higher frequencies.

Bubble clouds near the surface have been divided into three distinct classes. Tenuous bubble clouds are almost acoustically transparent, with only a small impedance mismatch between the outside and inside. However, they are large, deep, and common, so they may be responsible for low frequency scattering. Dense bubble clouds occur when waves break. They are acoustically dense and their buoyancy makes them hydrodynamically active. They have short time scales (measured in CST-7 by Farmer, and elsewhere by Melville). These time scales are incompatible with the persistence of scattering features seen in CST-7 by Gauss and Huster, and inconsistent with Gauss's frequency shift measurements when realistic parameters are assumed. The third possible class of bubble scatterers is intermediate between the first two types; they are acoustically dense, but hydrodynamically passive. These would have large target strengths and unknown lifetimes. Intermediate clouds have not been observed; Farmer probably would have seen them if they occurred under most "beta" whitecaps, as suggested by Monahan. No study has been done to see if their absence from data makes them too rare to dominate the reverberation. There appears to have been considerable reluctance to make the distinction between dense and intermediate clouds by researchers in the ONR surface reverberation SRP.

We consider scattering from tenuous clouds to most likely be the dominant backscattering mechanism at low frequencies. From CST-7, we learned that tenuous clouds are very intermittent. Most of the bubble cloud measurements give reverberation estimates that lie below the observed values. However, one bubble cloud event alone in CST-7 compensated for the remaining high sea state measurements when the average was taken. Thus, it requires an unreasonably large sample to make a convincing statistical comparison. For this reason, our deterministic comparison between bubble and reverberation measurements in CABEX is very important.

Previous investigators have emphasized using the scattering strength obtained from reverberation data to test models. From a scientific and applied point of view, other features of the data are at least as important. These features include the spatially intermittent nature of the reverberation and the frequency shift and spread (which may include mechanisms other than Doppler) properties.

Sound Velocity Measurements

It became clear from our work on near surface zone backscattering measurements that we need better measurements of the sound velocity in this region, where sound velocity reduction due to bubbles occurs. The velocity reductions are known to be dispersive, hence the measurements must be made at low frequencies. Ewart proposed making accurate measurements at 2 kHz, below the region of dispersion. The idea was tested analytically and numerically by Dashen Fan, one of Ewart's students, and was presented in D. Fan's Master's research project (M.S. awarded, '92). It was concluded that the technique would be effective and very accurate.

Nonlinear Imaging Methods

Several methods were developed for imaging using spatially diverse source and receiver arrays. These include the standard Bartlett, one based on third moments of the received complex field, and one based on locating the spatial position of maxima in the coherently summed receiver returns. Of these, the latter shows the most promise at improved resolution at lower frequencies. This development led to CABEX and IBEX, and is one of the major components of our future experimental program.

Wave Propagation in Random Media

Modeling

We have shown that moment theory adequately predicts the single frequency intensity variances from the MATE experiment. Two major deficiencies in the theoretical predictions are that the theory is not capable of predicting the two frequency cross-correlation of intensity, and that excessive computational complexity is required for long range predictions. Our current and proposed work focuses on overcoming these defects.

We can now confidently simulate three-dimensional linear internal wave fields. The field statistics have been calculated and shown to agree with those of the Garrett-Munk model in space/time. When combined with our pulse propagation codes, these simulated fields provide the capability to realistically simulate long range ocean scattering in space/time.

We have developed and implemented a method for directly solving the fourth moment equation for a plane wave initial condition. The results have been verified by comparing them to both theoretical predictions and acoustic scattering simulations. This is the first step toward evaluating the frequency cross correlation moments.

We have shown that the current theoretical formalism is not capable of predicting the moment statistics for an upper turning point in an ocean wave guide. This is essentially the problem of scattering due to a ray turning within a single medium irregularity. Uscinski has developed a model which we believed would allow us to address this question; that model has proved to be inadequate.

The two volume experiments, AATE (1985) and MATE (1977), provide temporal and spatial observations of the acoustic field moments where the statistics of the scattering environment are well known. AATE was an underice experiment where the acoustic field statistics provide a test of weak (Rytov) scattering theory. Predictions of the observed variances and temporal spectra of the phase and amplitude agree with experimental results for a 3-day record, but new formalism is required to account for the highly inhomogeneous scattering in the vertical, and the lack of temporal stationarity. The fourth moment theory developed in this program has been used to predict the stronger scattering observed during MATE. The intensity variances observed

over the deeper path have been adequately predicted. However, the two-point spatial and two-frequency statistics require further work.

Source Localization

Simulations and theory have been used to study the effect of volume forward scattering due to deep-water internal waves on matched-field processing. Second-moment theory has been applied to the case of quadratic average sound speed profiles. Monte Carlo simulations have been used to check the analysis, and will be used to see if analytical results hold up in more realistic environments. A paper (Jackson, D. and T. Ewart, The effects of internal waves on matched field processing) was published in JASA.

Probability Distributions

We have developed a model of the probability distribution of intensity for volume scattering. This model is based on a generalized gamma distribution and has been used to model the probability distributions due to a point source. This represents the only known model of the intensity distribution for ocean acoustic propagation. We completed work on research to provide an approximate analytical model for the intensity pdf for WPRM. This gives signal processors a method for including the highly non-Gaussian pdf's in their algorithms. Gordon, Ritcey, and Ewart developed a model for the pdf of the quadrature components of the field for WPRM. The model includes those scattering regimes where the pdf is highly non-Gaussian. Virtually all signal processing literature imposes a Gaussian quadrature component (exponential intensity pdf) on the methodology. The importance of the non-Gaussian pdf's remains to be decided for specific range/frequency ocean regimes. A paper by Gordon, Ritcey, and Ewart has been submitted to JASA.

Acoustic Propagation

Range Dependent Ray Trace

We have developed a computer code based on a Hamiltonian method for ray tracing. This code allows us to trace wave equation rays, PE rays, or wide-angle PE rays. The latter two are used in studies where we compare the results of ray tracing with those of PE codes. The code not only computes the rays, but also solves the Jacobi equation for the ray perturbations, and calculates the travel time. Although it was developed primarily for range dependent applications, it runs several times faster than a Snell's Law code for a range-independent calculation. We added a module to calculate the semiclassical wave function using the ray trace code output. Near caustics, this module uses the proper Airy functions, avoiding the infinite intensity of the standard ray trace method. The code is highly accurate; over a range of 30 megameters in a Munk profile, the turning point depth was exact to the nearest millimeter.

Depth-Angle and Time-Frequency Visualization of Wave Fields: The Wigner Function

The Wigner function provides a display of the angular spectrum or the frequency spectrum of a signal as a function of space or time. We have developed a computer code to calculate the Wigner function. The cross terms in the Wigner function are a major problem in e.g. time-frequency analysis, and the literature is filled with attempts to get around that problem. For the examples examined so far in our work, the ordinary Wigner function has been adequate. In Figure 2, we show the Wigner function of a 300 km PE propagation (400 Hz) through a range independent ocean as a depth/angle plot. This is superimposed on a depth/angle plot computed using the Hamiltonian method ray trace code. The figure demonstrates that ray tracing works well for the frequency-range combination. Additional high points in the Wigner function arise from the well-known interference forms.

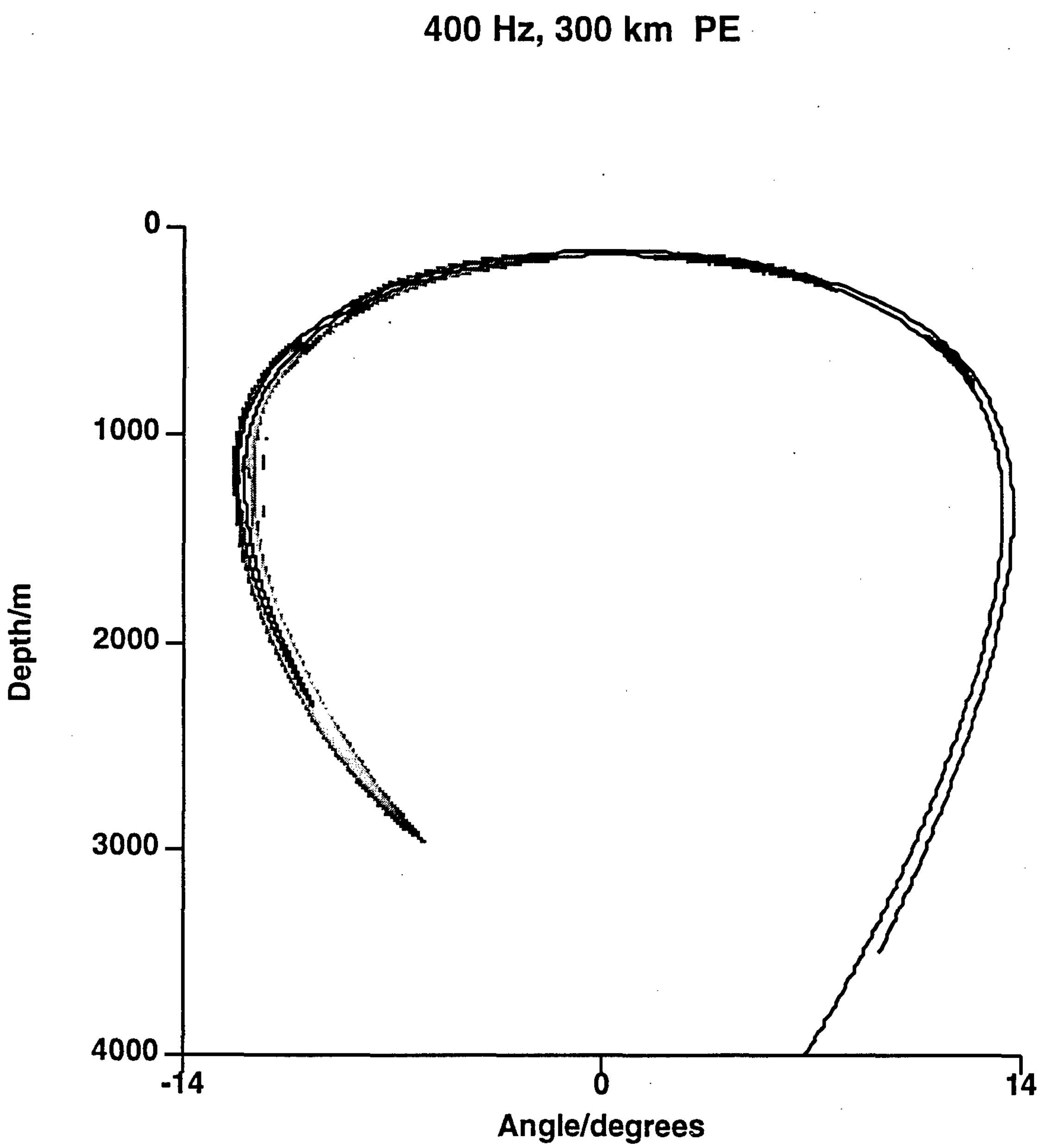


Figure 2.Wigner function for 400 Hz propagation to 300 km. PE results compared with PE ray trace results. (Plotted as depth/angle diagram)

Mode Propagation Code

A mode-propagation code was developed for the case of a range independent profile. By projecting the PE-source on the modal solution, results from the mode and PE solvers can be directly compared. For a source at 200 m, 500 modes were needed to verify a 300 km, 400 Hz case. The 500 modes were obtained in about 15 minutes on the MDG's Stardent computer. The field at any range is easily evaluated.

TRANSITIONS

Our 6.1 work has applications to 6.2 and 6.3 efforts. We were involved in the CST-7 experiment, which demonstrated that collaboration between 6.1 and 6.3 can benefit both programs. We had a major role in preparing "the hypothesis testing" document that facilitated the experiment planning and interpretation. Progress from CST-7 and CABEX is expected to lead to better algorithms for LFA reverberation mitigation.

We were involved in the FOSS component of CST-7, in which the near-surface acoustic field was measured and modeled. The CST sources gave us a signal that we believe can be exploited to define a characteristic signature of the surface zone reverberation.

We attended a workshop (NUWC, 31 March 1993) on forward surface scattering, where we presented an overview of our modeling. We are interested in collaborating with 6.3 activities in this area; by working closely with such an experimental program, we would be able to verify our models. We would contribute methods for interpreting experimental results, and suggest features of the experiment that will reveal the underlying physics.

Our modeling of surface forward scattering (including bubble cloud effects) and WPRM through the internal wave field provides insight that can be exploited when building new sonar systems. "Ribbons" of high intensity can be selectively used to enhance the signal to noise ratio; sonars have been built in the UK exploiting this feature. Sonar developers need to know the sound field vertical coherence length; in fact, we have more to offer. An expected intensity-travel time correlation can be used to remove the incoherence related to intensity, possibly enlarging the effective vertical coherence scale. Our studies of the probability density function of scintillation facilitate improvements of signal processing algorithms that usually have assumed Gaussian quadrature component fluctuations.

We have had a more broad-based involvement in the CST program as part of the surface scattering working group. Thorsos and Henyey are the only 6.1 scientists who regularly attend the working group's meetings, where much of the MDG's work has been presented.

A number of our studies are relevant to shallow water sonar systems. Surface and bottom forward scattering are important shallow water processes contributing to the difficulty of separating a large number of multipaths. Visualization techniques such as the Wigner function will play an important role in developing algorithms that can exploit both broad-band signals and wide apertures.

Ray tracing is the method of choice in most acoustic transmission applications. Our studies on the validity of ray tracing will induce greater confidence in ray tracing when warranted, and allow one to know when the results are unreliable.

Our experimental techniques and analysis methods could be useful in more applied situations. We can build and exploit three-dimensional transmit/receive arrays. Our "Acoustic Lego" method of putting together hardware could be exploited to make sonars that could easily be adapted to local conditions and tailored for

various uses. Our nonlinear imaging methods can be extended to operational sonar systems.

PUBLICATIONS and PRESENTATIONS

Many publications and presentations, many invited, were prepared during this grant period. They are documented in the annual reports to ONR, and will not be repeated here.